A COMPARISON OF WATER QUALITY EFFECTS OF MONTHLY AND ANNUALLY BASED POINT SOURCE LOAD REDUCTIONS

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Abstract

Chesapeake Bay physical and biological processes can be viewed as 'integrating' variations of nutrient load magnitude over time. The integration of loads over time ameliorates intra-annual load fluctuation, with the Bay responding to overall loads on an annual scale, and showing little response to monthly variations within an annual load. This may be due in part to water residence times of more than several months, estimated by a given parcel of water discharged at the mouth of the Chesapeake. Also, the time that a given nutrient load influences water quality, including recycling of nutrients from the sediments, is estimated to be of the order of several years or less. Water quality model findings of insignificant difference between constant monthly and variable monthly point source loads are consistent with the estimates and observations of the literature. Based on the various lines of evidence, annually based point source reductions are considered to be sufficient to protect Chesapeake Bay water quality; this is an important consideration for establishing point source discharge permits.

Observations from the Literature

Residence times of water, estimated by an 'age of water' model analysis, are on the order of three to four months for waters in the upper Bay (CB1TF) or the tidal fresh Potomac (POTTF) (Wang, 2003). Waters of the lower Chesapeake tributaries, such as the headwaters of the York River, have a residence time of about two months. The age of water analysis estimate is based on hydrodynamic modeling of the Chesapeake using a Lagrangian subroutine to track a particular water source within a larger Eularian hydrodynamic simulation. This gives a lower bound to the time that water and associated nutrient loads remain in the estuary, contributing in part to the Chesapeake Bay as an "integrator over time" of nutrient loads.

Nutrient residence times are longer than that of water. Nutrients are taken up by algae throughout the year, and once taken up, settle to the bottom to decay in the warmer summer waters, contributing to summer anoxia/hypoxia. Nutrient uptake in the winter and early spring is primarily by a concentric diatom phytoplankton community in the mesohaline region of the Bay. The annual peak of phytoplankton biomass, expressed as integrated water column chlorophyll *a* (>1,000 mg/m^2), occurs in the early spring, driven by the high flows and nutrient loads of the spring freshet (Harding et al., 2002). "The organic material of spring bloom origin subsequently provides the organic substrate for development of a robust microbial community whose metabolic activities delete oxygen (O_2) while regenerating nutrients that support a summer phytoplankton community" (ibid.). Estimates of the magnitude of nutrient regeneration from bottom sediments expressed as a percentage of the annual terrestrial plus atmospheric inputs is given by Boynton et al. (1995) as 55% to 233%, and 44% to 214%, for nitrogen and phosphorus respectively.

Bottom nutrient releases come from organic nitrogen and phosphorus that have been deposited over a period of at least two years. Boynton et al. (1995) estimated "...annual mean pool sizes for nitrogen and phosphorus in the water column, sediments (top 5 cm of the sediment column), and biota ... for the 1985-1986 period ... to have 87% of the TN in the sediments, 12% in the water column, and <1% in the biota. Stocks of TP are similarly distributed, but sediment stocks are even more dominant." Boynton et al. considered the upper 5 cm of the sediment to be as important as the first few millimeters because of mixing of the upper layers of sediment by bioturbation and resuspension.

From this, it is clear that summer anoxia is the result of organics, primarily from algal primary production, which deposit in sediments throughout the year, with peak algal biomass generated in the spring bloom. Organics from algal primary production are stored in Chesapeake sediments throughout the year and between years. "These results suggest that the coupling between nutrient loading, water column production of organic matter, and recycling of nutrients from sediments occurs over time scales of about several years or less" (Boynton et al., 1995).

Estimates from the Model

The complex movement of water within the Chesapeake Bay, particularly the density-driven vertical estuarine stratification, is simulated using a Chesapeake Bay hydrodynamic model (CH3D finite-difference hydrodynamic model) of more than 13,000 cells (Johnson et al., 1993). The Water Quality Model (CE-QUALICM finite-volume water quality model) is linked to the hydrodynamic model and uses complex nonlinear equations describing 26 state variables of relevance to the simulation of dissolved oxygen, water clarity and chlorophyll *a* (Cerco and Cole, 1994). Coupled with the Water Quality Model are simulations of settling organic material sediment and its subsequent decay and the flux of inorganic nutrients from the sediment, as well as a coupled simulation of underwater Bay grasses in the shallows. The model is run for 10 years using 1985-1994 hydrology, with 15-minute time-step and outputs of daily or monthly water quality. The 2002 version (13,000 cells) three-dimensional Chesapeake Bay Estuary Model (CBEM) is applied in this analysis.

A model run to examine the differences between a constant monthly load and a variable monthly nitrogen load, but each at the same annual load levels, was completed. The constant monthly discharge estimate is based on a management scenario (Tier 3) which assumes a level of point source loads based on a constant 5 mg/l TN discharge applied against point source flow. The variable monthly load scenario is based on records of 54 Chesapeake Bay sewage treatment plants (STPs) which use Biological Nutrient Removal (BNR) treatment and have complete monthly records. The total nitrogen average concentration for each month of the 54 BNR STPs (which annually achieved about an 8 mg/l average concentration) was calculated and then converted to a concentration that would be at the same level of annual loads as the constant 5 mg/l case, yet still preserve the observed monthly variations. Monthly changes in flow were also taken into account. The variation in monthly concentrations calculated with this method varied from a low of 3.76 mg/l in August to a high of 8.46 mg/l in January. The derived monthly variation, equivalent on an annual basis to the constant 5 mg/l monthly loads, was applied to all point source dischargers in the Chesapeake watershed. To compare the two scenarios, recently developed water quality criteria were used. Water quality results of the two scenarios were indistinguishable. No difference was seen in the achievement of Chesapeake water quality criteria.

A similar model run was made with variable monthly total phosphorus loads from STPs. The variable monthly load was based on the variation seen in the 2002 discharged loads of phosphorus, which varied from a low of 0.86 of the Tier 3 constant STP load in January, to a high of 1.10 of the Tier 3 constant STP load in June. The monthly variable load scenario had the same annual load as the Tier 3 scenario. As with the scenario of variable monthly nitrogen loads, no difference was seen in the achievement of Chesapeake Water quality criteria between the scenarios of constant or variable TP monthly loads.

Application

The EPA has developed water quality criteria for DO, clarity, and chlorophyll designed to protect water quality in Chesapeake Bay and its tidal tributaries (U.S. EPA, 2003). The main cause of water quality impairment for these parameters in the main stem of the Bay is loading of nutrients, specifically nitrogen and phosphorus, from point and non-point sources throughout the entire Chesapeake Bay watershed. The EPA is in the process of developing wasteload allocations for point sources discharging into the Bay and its tributaries that are designed to protect water quality in the main stem of the Bay.

Establishing appropriate permit limits that implement these wasteload allocations for discharges that cause, have the reasonable potential to cause, or contribute to excursions of water quality criteria for the main stem of Chesapeake Bay is different from setting limits for other parameters such as toxic pollutants. This is due to: 1) the exposure period of concern for nutrients loadings to this part of the Bay is very long; 2) the area of concern is far-field (as opposed to the immediate vicinity of the discharge); and 3) the average pollutant load rather than the maximum pollutant load is of concern. Thus, developing appropriate effluent limitations requires innovative implementation procedures.

The present paper does not address wasteload allocations to meet other water quality standards in areas outside of the major Chesapeake Bay segments. This approach also does not apply to parameters other than nitrogen and phosphorus that may exhibit an oxygen demand to other waters of the Bay, such as dissolved oxygen, biochemical oxygen demand, and ammonia among others.

Of course, all local water quality standards apply and must be met when evaluating appropriate point source permit effluent limits. State water quality standards for nutrients to be applied to local waters are being developed as stand-alone criteria. In any case, where the nutrient wasteload allocations for protection of water quality in a river, tributary, or other part of Chesapeake Bay are expressed as a shorter term criterion, i.e., seasonal, monthly, weekly or daily values, the permit limits that derive from and comply with that wasteload allocation designed to protect those criteria must be used. Shorter averaging periods might be appropriate and necessary to protect against local nutrient impacts in rivers or streams in the basin.

Additionally, it is important to note that the nutrient dynamics of the Bay may not be unique, so the establishment of an annual limit with a similar finding of "impracticability" (pursuant to 40 CFR 122.45(d)) may be appropriate for the implementation of other nutrient criteria in other watersheds where attainment of the criteria depends on long-term average loadings rather than short-term maximum loadings. Annual limits may be considered when technically supportable with robust data and modeling as they are in the Chesapeake Bay context, and appropriate safeguards to protect all other applicable water quality standards are employed.

The nutrient dynamics of Chesapeake Bay are complex. Unlike toxics and many conventional pollutants that have a direct and somewhat immediate effect on the aquatic system, nutrients have no direct effect, but instead are 'processed' in several discreet steps in the Bay ecosystem before their full effect is expressed. Each processing 'step' further delays and buffers the time between the time of nutrient discharge in an effluent and the resultant nutrient effect on the receiving water body. More specifically, nutrients are taken up by algae throughout the year, and once taken up, settle to the bottom to decay in the warmer summer waters, contributing to summer anoxia/hypoxia. Thus, summer anoxia is the result of organics, primarily from algal deposition, which accumulates throughout the year, with peak algal biomass generated in the bloom of early spring, and that these organics are stored in Chesapeake Bay sediments throughout the year and between years. Chesapeake Bay's biological and physical processes can be viewed as 'integrating' variations of nutrient load magnitude over time. The integration of nutrient loads from all sources over time ameliorates intra-annual load fluctuations from individual sources, with the

Bay responding to overall loads on an annual scale, while showing little response to monthly variations within an annual load.

The NPDES regulations at 40 CFR 122.45(d) require that all permit limits be expressed, unless impracticable, as both average monthly limits (AMLs) and maximum daily limits (MDLs) for all dischargers other than publicly owned treatment works (POTWs), and as average weekly limits (AWLs) and AMLs for POTWs. For nutrient effects in the main stem of the Bay, the long-term average loading rather than short-term maximum loadings are of concern. As the results of the water quality modeling of point source loading of nutrients in the Chesapeake Bay indicated, effluent limitations for nitrogen and phosphorus expressed as daily, weekly or monthly averages would provide no additional value for the protection of water quality standards of the main Bay.

Conclusions

The literature is replete with descriptions of Chesapeake processes that integrate or ameliorate fluctuations of nutrient loads over relatively short periods of time, responding to the total load over time rather than short term variations. The Chesapeake integrates variable monthly loads over time, so that as long as a particular annual total load is met, constant or variable *intra-annual* load variations appear to be relatively inconsequential.

A cautionary note here is warranted. The integration of nutrient loads over time is seen at the scale of the model analysis of the water quality criteria which uses about seventy large-scale regions of the Bay to examine water quality effects. Smaller scales, such as embayments and smaller tributaries, were unexamined. Of course, all local water quality standards apply and must be met when evaluating point source annual permit limits.

Resident times of water based on 'age of water analysis' estimate that a parcel of water would take more than several months before being discharged at the Bay mouth. Nutrient mass balances of the Chesapeake estimate that coupling between nutrient loading, production of organic matter, and recycling of nutrients from the sediments occurs over time scales of several years or less. Model scenario findings of insignificant differences between constant monthly and variable monthly point source loads are consistent with the estimates and observations of the literature. Based on the various lines of evidence, and at the scales applied to examine Chesapeake water quality criteria, annually based point source nutrient reductions are sufficient to protect Chesapeake Bay water quality.

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